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How Can We Make PV Modules Safer?

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***Abstract* — Safety is a prime concern for the photovoltaics (PV) industry. As a technology deployed on residential and commercial buildings, it is critical that PV not cause damage to the buildings nor harm the occupants. Many of the PV systems on buildings are of sufficiently high voltage (300 to 600 Volts dc) that they may present potential hazards. These PV systems must be safe in terms of mechanical damage (nothing falls on someone), shock hazard (no risk of electrical shock when touching an exposed circuit element), and fire (the modules neither cause nor promote a fire). The present safety standards (IEC 61730 and UL 1703) do a good job of providing for design rules and test requirements for mechanical, shock, and spread of flame dangers. However, neither standard addresses the issue of electrical arcing within a module that can cause a fire. To make PV modules, they must be designed, built, and installed with an emphasis on minimizing the potential for open circuits and ground faults. This paper provides recommendations on redundant connection designs, robust mounting methods, and changes to the safety standards to yield safer PV modules.**

***Index Terms* — photovoltaic modules, fire hazards, shock hazards**

I. Introduction

Safety of photovoltaic (PV) systems is critical to the commercial success of PV. Safety issues could lead to rejection of PV by consumers, inspectors, regulatory authorities, financiers, and/or insurance companies. These issues are most important for PV on buildings or where there is potential exposure to the general population. Safety is not as critical for behind-the-fence utility-scale PV where exposure is significantly limited.

Some of the safety issues related to high voltages can be addressed at the systems level by:

- Limiting dc system voltages via the use of modular inverters or dc-to-dc converters on each module.
- Requiring dc arc detectors and interrupters on all high voltage PV systems as has been proposed for the National Electric Code.
- Leaving the array itself floating (not grounded) so the first ground fault does not cause a ground loop and can easily be detected by the ground fault detector and be repaired.

None of these is likely to be the solution for all PV systems. Modular inverters and dc-to-dc converters may have their own reliability issues, and it is not clear whether they can match the lowest cost achievable with central inverters. Today there are no commercially available dc arc detectors certified to UL 1699B [1] nor do the prototypes under development detect and interrupt all types of dc arcs.

In order to make all PV systems safer, a redesign of the PV module itself is proposed. Developing PV modules that are inherently safer can improve the safety of all PV systems. To begin the process, this paper will discuss how modules can be dangerous and then look at today's module safety standards to better understand the safety gaps that remain to be addressed.

II. How Modules Can Be Dangerous

There are three main areas of concern for PV module safety:

1. Shock hazard: Someone touches exposed high voltage.
2. Mechanical Safety: The module or parts of the module fall on someone, or ice or snow falls off of the module onto someone.
3. Fire Safety: The module can either spread a fire that started somewhere else or start a fire itself.

III. Module Safety Testing

Modules are safety tested to either IEC 61730 [2] or UL 1703 [3] or both. Both have similar requirements, including design criteria, testing of materials, and testing of completed modules. Both do a good job of requiring designs that minimize electric shock, mechanical problems, and the spread of flames. Each contains tests that should identify shock hazards and mechanical problems and include spread of flame tests. Neither addresses the issue of modules starting a fire. An effort is now underway to modify IEC 61730 to improve the way it handles the potential for a module to cause a fire. The rest of this paper will discuss proposed solutions to mitigate the fire danger and provide technical information to support the proposed changes to IEC 61730.

IV. PV Module Fire Hazards

There are three typical ways that a module can overheat. Each is discussed along with the probability that it can cause a sustainable fire within the module.

A. Hot Spots

A hot spot can occur when a cell (or cells) are forced into reverse bias because it (they) cannot carry the peak power current being produced by the other cells in series. Hot spots can be caused by poor cell matching, cracks, localized soiling (bird droppings), or shadowing. Cells are supposed to be protected by the bypass diodes that limit the reverse voltage across a cell to less than ~ 10 volts. Problems can occur when the bypass diodes fail or are never installed correctly or when the cells have very low shunt resistances and therefore overheat at 10 volts reverse bias before the diodes activate.

Figure 1 shows an example of reverse bias leakage current measured on 50 commercial cells at -10 volts, the approximate voltage level that occurs when 20 cells are protected by one bypass diode. Figure 2 shows an IR picture of six cells with high leakage currents from the set in Figure 1 [4]. The highest measured temperature was less than 100°C. So, for these cells, using adequate bypass diode protection (no more than 20 cells per bypass diode) and screening for low shunt cells should limit the temperature increase and not cause a sustained fire.

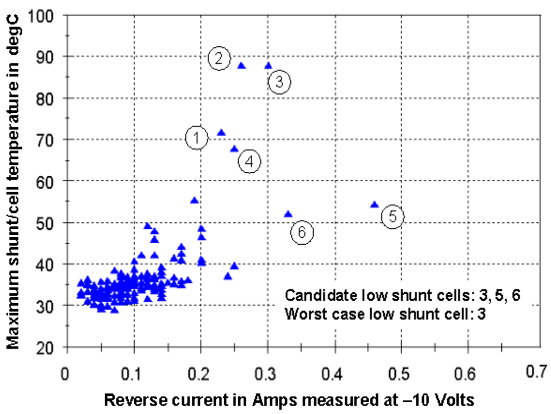

Fig. 1. Reverse leakage current for 50 commercial cells biased at -10 volts.

On the other hand, if the shunt path is localized enough and the cells are not adequately protected with bypass diodes, hot spots can melt silicon. While such events are hot enough to melt/decompose encapsulants and backsheets, in most cases they quickly result in total shunting of the junction and elimination of the hot spot. Cunningham claimed that neither hot spots nor resistive heating are likely to lead to sustained fires in PV modules [5].

Recent results, however, indicate that as cells and modules get larger, this may no longer be the case. Figure 3 shows the result of a hot spot occurring within a large module with 72 15.6 cm by 15.6 cm solar cells. The cell shown in the picture has suffered a hot spot that was so severe that it burned a significant area of the cell and broke the glass. In this case the bypass diode protecting the string containing the damaged cell was still functional. So this failure was caused by the power produced in the 24-cell string protected by the diode. For large cells, module manufacturers may have to either use fewer cells per diode or improve their screening of cells with low shunt regions as described in the section on Improving Module Design and Construction.

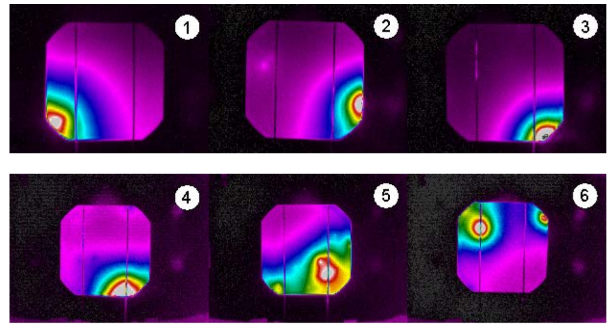

Fig. 2. IR pictures of the six cells with highest reverse leakage current and temperature increase when biased at -10 volts.

Fig. 3. Burned area in module caused by hot spot.

B. High Series Resistance

Failure of solder bonds within the module can lead to overheating at the failing solder bond in addition to the remaining bonds that are left to carry the additional current as shown in Fig. 4. Such high resistance bonds do lead to significant output power loss. However, the temperatures reached at these weak solder bonds are typically not high enough to cause fires. The danger comes when the resistive heating results in total failure of all of the bonds connecting an individual cell, resulting in an open circuit, which can lead to an arc.

C. Arcing

Two types of arcing can occur within a PV module:

1. Series arcs are caused by an open circuit in a high-voltage dc array. In a PV module a series arc can occur whenever the current path is disrupted. Examples include when one of the output leads loses electrical conductivity to the cell circuit as shown in Fig. 5, or when the second interconnect on a cell fails and the bypass diode is not operational as shown in Fig. 6. Series arcs are reasonably easy to detect and can be

stopped by opening the series circuit in which they are occurring.

2. Parallel arcs occur when two different dc polarities come in close proximity. In a PV module, a parallel arc can occur due to a ground fault. Parallel arcs are more difficult to detect and much more difficult to stop, as the current flow is either directly from plus to minus or through a ground loop.

No material selection or module design is going to prevent a module from catching fire once an arc is sustained because of the extremely high temperatures within an arc.

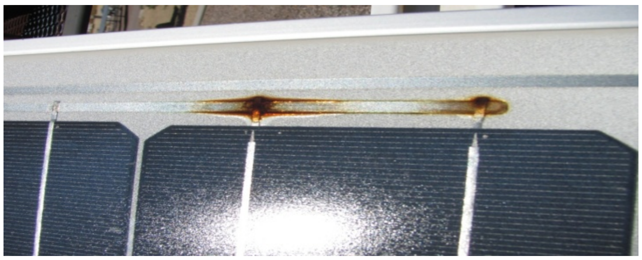

Fig. 4. Resistive heating of solder bonds connecting two ribbons from the same cell.

Fig. 5. An arc caused by failure of the solder bond that attached an output lead to the module circuitry.

IV. Improving Module Design and Construction

A. Stopping Open Circuits from Occurring

The first step in reducing the potential for open circuits within the module is to design modules with redundant electrical connections so that it takes multiple failures to cause an open circuit. For crystalline silicon modules, most cells are tabbed with multiple (two, three, four, or even five) tabbing ribbons each soldered at multiple locations or otherwise electrically bonded to the cell over a large area. This provides redundancy and protection against open circuiting.

Bypass diodes provide an additional level of protection, as they should carry current around any failed connections within the cell matrix. To ensure that this safety feature of the bypass diodes is functioning, the diode function should be checked on each new module before it is shipped from the factory. In addition, bypass diodes are recommended on all modules, including thin films regardless of whether or not they are necessary to protect against hot spots.

Fig. 6. An arc across the broken interconnect on a cell.

The most likely place for an open circuit to occur in a module is at the output leads because:

- These connections are usually not protected by bypass diodes;
- Often they are not redundant;
- Typically the process for these connections is manual; and
- They can be the connections with the most stress as they interface with the rest of the PV system.

To improve the design, the next edition of IEC 61730 has been written to require redundant types of soldered interconnects at the output leads. For example, the module could be designed to have both a mechanical clip and a solder bond to meet the requirement. Other types of module termination will be subjected to design criteria (such as pressure from a polymeric material cannot be used as the means for holding a connection together) and testing as detailed in EN 50548 [6].

Finally, with the output connection and all electrical connections, design for manufacturing, process control, and personnel training are very important. The manufacturing process should be easy to perform and easy to inspect to ensure that the electrical connections have been made to specification.

B. Stopping Ground Faults from Occurring

The majority of ground faults are installation related. Improved installation safety requires improved installer training, improved installation documentation, and publication of installation safety standards. Module mounting systems should follow specific design rules that forbid the attachment of conductive mounting hardware directly onto polymeric backsheets behind solar cells and/or other components of the electric circuit. Module framing should be mounted outside of the active area, meeting the creepage and clearance distances for the rated system voltage.

Module manufacturers (for both crystalline silicon and thin film modules) should pay particular attention to adhesion between encapsulant and glass. Electrical leakage from active circuit to the ground plane along a delamination between encapsulant and glass is a failure mode observed in the field. Such leakage is a shock hazard if the mounting system is not grounded and a ground fault hazard if it is grounded. The solution to this problem is a robust manufacturing process with good process control and QA system.

C. Bypass Diode Protection and Cell Screening

The number of cells per bypass diode establishes the maximum reverse voltage that a shadowed cell will see. Each cell must be capable of surviving a reverse voltage equal to the sum of the forward voltages of all of the other cells protected by that diode while passing approximately peak power current. In a module with 20 cells per diode, this means each cell must be capable of surviving the voltage provided by the other 19. However, if there are more cells per bypass diode, say 24 like in Fig. 3, then the reverse voltage will be higher, equal to the voltage provided by the other 23. Especially in high-current modules, this can represent a significant amount of power dissipated in a small area. For the module in Fig. 3 it would not be unusual to have a shadowed cell dissipating 100 watts.

This level of power dissipation could easily result in overheating of a localized shunt. In order to prevent overheating, cells should be screened to eliminate hot spots. This can be done by sorting out low shunt resistance cells by measuring the leakage current under reverse bias conditions or by sorting out cells with hot spots as measured by a fast infrared camera under reverse bias conditions. Shunt screening is probably easier but not as effective because cells with fairly high shunt resistance (> 10 Ohms) can still have localized hot spots that may overheat. Use of manufacturing screening tools to sort by hot spots is the most effective approach.

Historically, modules used 24 cells per bypass diode. However, as the cells have gotten larger they must dissipate more power, so it is very important to test the design using a Hot Spot Test. The Hot Spot Test in the present IEC Qualification Standard – IEC 61215 Edition 2 [7] is not a good test for determining if a particular cell/diode combination is adequate because the cell selection does not test the most susceptible cells [4]. The Hot Spot Test in the draft of IEC 61215 Edition 3 or the test in ASTM E2481 will do a much better job of determining whether the selected bypass diode design is adequate. To ensure the best performance, the Hot Spot Test should be performed using cells that represent the borderline of screening; that is, use cells with the lowest shunt resistance or the highest hot spot temperature allowed for the product under test.

V. Conclusions

Making modules inherently safer with minimum additional cost is the preferred approach for PV. Safety starts with:

- Proper screening to remove cells with hot spots or low shunt resistances;
- Module design to ensure adequate bypass diode protection so that cells within specification with the worst case allowable hot spots or lowest acceptable shunt resistances can survive the IEC 61215 Edition 3 or ASTM E2481 Hot Spot Tests;
- Module design to ensure redundancy within the electrical interconnection to minimize open circuits;
- Electrical termination meeting the requirements of the EN 50548 J-box standard; and
- Proper installation protocol to prevent installation related ground faults.

Module manufacturers must control the raw materials and processes to ensure that that every module is built like those qualified through the safety tests, the reason behind the QA task force effort to develop a "Guideline for PV Module Manufacturing QA." Periodic accelerated stress testing of production products is critical to validate the continued safety of the products being produced.

Combining safer PV modules with better system designs and the use of lower voltage circuits and arc fault detectors/ interrupters can solve many of the safety problems observed with today's PV systems.

Acknowledgments

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